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Sustainable Advances in Phosphorus Removal and Recovery from Industrial Wastewater

Md Adim[1], Mohd Imran Siddiqui[2], Hasan Rameez[3], Izharul Haq Farooqi[4] and Farrukh Basheer[5]†

Department of Civil Engineering, Zakir Husain College of Engineering and Technology, Aligarh Muslim University, Aligarh 202002, India

†Corresponding author: Farrukh Basheer; farrukhbasheer.cv@amu.ac.in

ORCID IDs of Authors: [1]ORCID: https://orcid.org/0009-0004-1746-3412; [2]ORCID: https://orcid.org/0000-0002-8310-0335; [3]ORCID: https://orcid.org/0000-0003-0400-5880; [4]ORCID: https://orcid.org/0000-0003-0601-7519 ; [5]ORCID: https://orcid.org/0000-0002-5932-9877

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ABSTRACT

Phosphorus, an essential nutrient and a finite resource, poses significant environmental challenges when discharged into water bodies from industrial wastewater, contributing to eutrophication and ecosystem degradation. Concurrently, its recovery offers a sustainable pathway to address resource scarcity. This review critically evaluates recent progress in phosphorus removal and recovery technologies, emphasizing five widely recognized approaches: (i) biological processes, such as aerobic granular sludge and enhanced biological phosphorus removal (EBPR); (ii) chemical precipitation using agents like lime and metal salts; (iii) struvite crystallization; (iv) electrocoagulation (EC) and (v) Bioelectrochemical Systems (BES)-for phosphorus recovery. The assessment focuses on these methods' efficiency, feasibility, and sustainability, highlighting their strengths and limitations. These strategies can foster eco-friendly wastewater treatment, mitigate eutrophication risks, and reduce dependence on finite phosphate resources.

1. Introduction

The rapid growth of industry and urbanization has led to the discharge of phosphorus-rich wastewater, leading to eutrophication in water bodies. Excessive Phosphorus promotes harmful algal blooms (HABs), which deplete oxygen and release toxins like microcystin, threatening aquatic ecosystems (Wang et al. 2024). Effective phosphorus removal and recovery strategies are essential to mitigate these environmental impacts.

1.1. Sources and Challenges in Phosphorus Removal from Wastewater

Phosphorus primarily enters wastewater from agricultural runoff, industrial effluents, and domestic sewage. Industries such as slaughterhouses, food processing plants, and fertilizer production facilities contribute high concentrations of organic matter and Phosphorus, necessitating efficient treatment solutions (Cao & Mehrvar, 2011). Removing Phosphorus from wastewater is generally achieved through physicochemical or biological methods to enhance phosphorus elimination (Mahvi et al. 2011).

Biological phosphorus removal generally relies on enhanced biological phosphorus removal (EBPR). In this method, specific microorganisms known as polyphosphate-accumulating organisms (PAOs) play a key role. These PAOs absorb Phosphorus from the water and store it inside their cells as polyphosphate. While EBPR is cost-effective and sustainable, it requires large reactor capacities, high biomass concentrations, long hydraulic retention times (HRT), and precise sludge management (Bazrafshan et al. 2012).

Conventionally, phosphorus removal relied on chemical precipitation, which required additional coagulants such as lime ($Ca\ (OH)_2$), ferric chloride ($FeCl_3$), or aluminum sulfate ($Al_2(SO_4)_3$) (Mahvi et al. 2011). While effective, these methods generate substantial sludge, leading to high disposal costs and potential secondary pollution (Drogui et al. 2008). As a result, there is an increasing need for integrated and sustainable approaches that optimize phosphorus removal while ensuring economic and environmental viability.

1.2. Phosphorus Recovery: A Sustainable Solution

Phosphorus (P) is a non-renewable resource essential for every living organism (Van Phuong, 2025). It constitutes approximately 2-4% of the total solid mass of biological organisms and serves as a crucial nutrient for all life forms, playing a pivotal role in shaping genetic components (Karl, 2000). Phosphate rock, the primary source of naturally occurring Phosphorus, serves the fertilizer production industry to sustain global farming. However, phosphate rock reserves are depleting, raising concerns over long-term agricultural productivity. The US Geological Survey reports that approximately 73% of the world's phosphate reserves are concentrated in Morocco and Western Sahara, highlighting potential geopolitical and economic vulnerabilities in phosphorus supply (Fig. 1) (Jasinski, 2017; Kok et al. 2018).

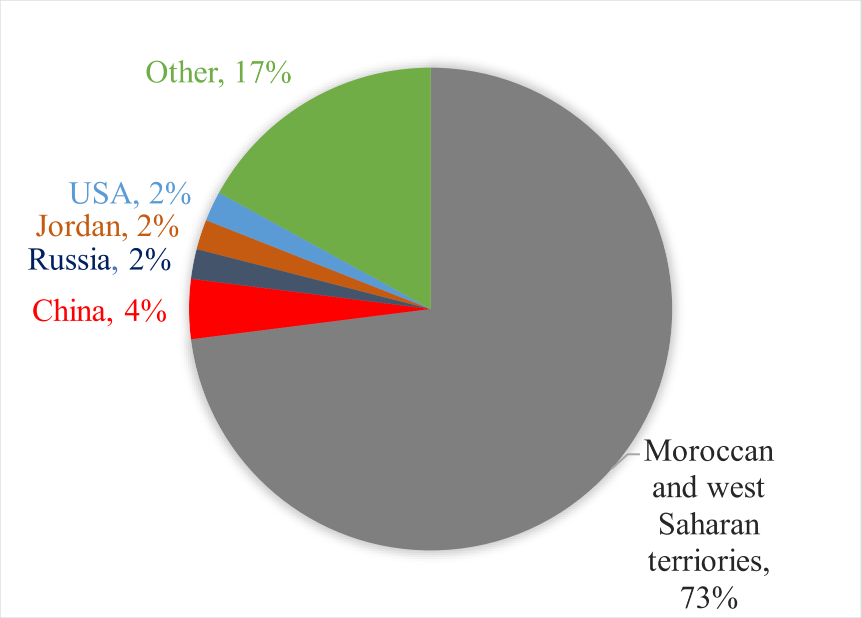


Fig. 1: Global distribution of estimated phosphorus reserves (Kok et al. 2018).

To address these challenges, phosphorus recovery from wastewater has emerged as a sustainable strategy. Studies estimate that 15-20% of the global phosphorus demand could be met through wastewater-derived phosphorus recovery, reducing dependency on phosphate rock mining while mitigating environmental pollution (Kok et al. 2018). Phosphorus in wastewater mainly exists as orthophosphates, and treatment plants can recover it through biological processes, chemical precipitation, adsorption, struvite crystallization, and Electrocoagulation (Wang et al. 2024).

1.3. Scope of This Review

Phosphorus fertilizers are essential for food security, contributing to nearly half of the world's food production (Grant et al. 2001; Cordell et al. 2009). Given the increasing global population and the limited availability of phosphate rock, improving phosphorus recovery from wastewater is imperative. Therefore, this review aims to provide an in-depth analysis of recent phosphorus removal and recovery technology advancements. The study will explore four key treatment approaches

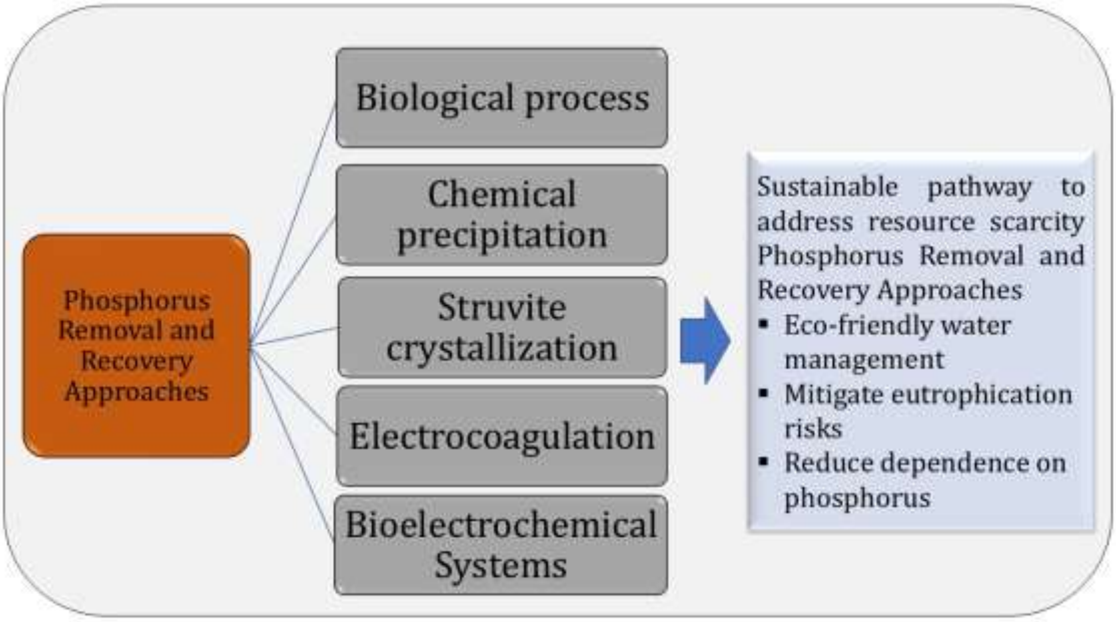
1. Biological processes – including Aerobic Granular Sludge (AGS) and Enhanced Biological Phosphorus Removal (EBPR)

2. Chemical precipitation – using lime and metal salts

3. Struvite crystallization – for simultaneous phosphorus recovery and reuse

4. Electrocoagulation (EC) – for efficient phosphorus removal

5. Bioelectrochemical Systems (BES)- for phosphorus recovery



This review highlights recent progress in sustainable phosphorus management and examines various phosphorus recovery methods, emphasizing their practicality, effectiveness, and cost-efficiency.

2. Methodology of Literature Review

This review was conducted using a systematic approach to ensure comprehensive coverage of phosphorus removal and recovery technologies. Relevant literature was collected from Scopus, Web of Science, ScienceDirect, and Google Scholar databases.

Keywords such as Phosphorus removal, Eutrophication, Wastewater treatment, Struvite crystallization, Electrocoagulation, and Bioelectro-chemical Systems were used.

Studies published between 1999 and 2025 were considered, with emphasis on recent developments.

Selection criteria included: (i) relevance to wastewater treatment, (ii) quantitative reporting of phosphorus removal/recovery, (iii) availability of operational and economic data.

A total of 105 peer-reviewed articles were critically analyzed using a multi-criteria evaluation framework.

Evaluation Framework for Comparative Analysis

A multi-criteria evaluation framework was developed to enable a systematic comparison of phosphorus removal and recovery technologies. The framework considers four key criteria: (i) removal efficiency, (ii) recovery potential, (iii) operational and economic considerations (including energy demand and chemical usage), and (iv) technology readiness level (TRL) and scalability.

2.1. Phosphorus concentrations in wastewater

Anaerobically digested swine wastewater has been reported to contain 612 mg/L Total Phosphorus (TP), with 36% (221 mg/L) present as dissolved phosphate (PO_4^{3-} -P) (Kim et al. 2017). Likewise, abattoir effluent has significant variability in TP concentrations, spanning from 15 to 785 mg/L (Ge et al. 2015; Lemaire et al. 2009).

In contrast, due to dilution effects, cellulose, tannery, and aquaculture industries exhibit significantly lower TP concentrations. The aquaculture sector, with large effluent volumes (10,000 million liters per day), has TP concentrations as low as 0.3–2.3 mg/L (Schulz et al. 2003), while tannery and cellulose wastewater typically report TP levels below 1 mg/L (Chamorro et al. 2010).

The proportion of phosphate within TP varies across industries. In tannery and aquaculture wastewater, phosphate constitutes 33% and 35% of TP, respectively (Kim et al. 2017; Lefebvre et al. 2005). The slaughter industry, however, demonstrates the highest proportion of phosphate, ranging from 85% to 95% of TP, with corresponding PO_4^{3-} –P concentrations between 25 and 230 mg/L (Lemaire et al. 2009; Ge et al. 2015; Ashraf & Farooqi, 2022).

Compared to industrial wastewater, residential wastewater generally exhibits lower total Phosphorus (TP) values, ranging from 5 to 30 mg/L, depending on whether the sources are urban or rural. However, a substantial portion (57–95%) of TP in domestic wastewater is inorganic phosphate (Andrés et al. 2018; Sengupta & Pandit, 2011; Pronk et al. 2015).

From an environmental perspective, even low TP concentrations (0.03–1 mg/L) in continental water bodies such as rivers and lakes can trigger eutrophication (Carrillo et al. 2020).

Table 1: Physicochemical Properties of Various Wastewater Categories (Carrillo et al. 2020; Ashraf & Farooqi, 2022)

Wastewater	pH	COD (mg/L)	TN (mg/L)	TP (mg/L)	PO_4^{3-}–P (mg/L)
Domestic	7.0–8.5	0.2–1.0	28–100	5.0–30	4.0–20
Abattoir	6.8–7.3	2.9–68	294–670[a]	28–49	23–40
Poultry	6.9–7.9	1.8–12	98–1825[a]	15–446	7.0–28
Swine	6.8–7.8	25–60	2350–3570	194–780	45–221
Dairy manure	7.0–8.3	1.2–38	65–3305[a]	12–266	8.5–13

Slaughterhouses	6.8-8.5	4.7-6.2	180-256[a]	-	130-256

a Values for Total Kjeldahl Nitrogen (TKN) fall within this range.

The physicochemical properties of various wastewater categories, including TP levels, are summarized in Table 1.

2.1. Analysis of Phosphorus in Wastewater

The ammonium molybdate spectrophotometric method, introduced in 1962, is widely recognized as a straightforward, reliable, and standard technique for measuring dissolved inorganic phosphorus (IP), such as orthophosphate, as well as total phosphorus (TP). Phosphorus concentrations can be phosphate or orthophosphate (PO_4^{3-}) or phosphate phosphorus (PO_4^{3-}-P). PO_4^{3-} denotes the number of orthophosphate molecules in a sample, Whereas PO_4^{3-}-P quantifies the number of phosphorus ions present in a sample (APHA 2012). The ascorbic acid method is commonly used to determine phosphorus in water. It involves the reaction of phosphate ions with molybdate ions (MoO_4^{2-}), forming phosphomolybdate $[PO_4Mo_{12}O_3]^{3-}$. When reduced by ascorbic acid, this compound produces a blue complex, which is measured using a spectrophotometer (APHA 2012).

Flow injection analysis (FIA), developed in 1975 (Ruzicka & Hansen, 1975), is a rapid, accurate, and automated technique for phosphorus (P) detection in water, utilizing the ammonium molybdate spectrophotometric method with a flow-through detector. Despite its advantages, FIA can be affected by metal ion interference and high salinity (Alam et al. 2021). Inductively coupled plasma (ICP) techniques, such as ICP-AES and ICP-MS, offer high sensitivity for elemental P detection, with ICP-MS achieving ultra-low detection limits (l g/L level) through high-resolution mass analyzers that mitigate interferences (Alam et al. 2021; Miller Ihli & Baker, 2001). Ion chromatography (IC), particularly ion-exchange chromatography with suppressed conductivity detection, provides high sensitivity and accuracy for phosphate and total phosphorus (TP) analysis (Lu et al. 2002; Ruiz-Calero & Galceran, 2005).

Gas chromatography (GC) and liquid chromatography (LC), commonly coupled with mass spectrometry (MS), are widely used for organophosphorus (OP) compound analysis, with LC-MS being especially effective for thermally unstable and polar OP species, achieving detection limits as low as ng/L (Gao et al. 2013; Wang et al. 2009). Additionally, spectroscopic techniques such as 31P-NMR allow non-destructive qualitative and quantitative analysis of P species, though they exhibit higher detection limits (mg/L level) and are susceptible to matrix interferences (Cade-Menun, 2005; Chen et al. 1999). Each method presents distinct advantages for P analysis in wastewater, with FIA and IC being rapid and sensitive, ICP offering elemental specificity, GC/LC-MS excelling in OP detection, and 31P-NMR providing valuable structural insights.

3.Treatment technologies

3.1. Biological process

Biological Processes Biological phosphorus removal involves the use of microorganisms to uptake and store phosphorus.

Granular Sludge (AGS): A biofilm-based system where microbial granules form under aerobic conditions, enhancing nutrient removal efficiency.

Enhanced Biological Phosphorus Removal (EBPR): A process that uses polyphosphate-accumulating organisms (PAOs) to store phosphorus as intracellular polyphosphate. PAOs uptake phosphorus under aerobic conditions and release it under anaerobic conditions, enabling efficient removal and recovery.

3.1.1. Aerobic granular sludge

Aerobic granular sludge (ASG) is a biological system containing bacteria, protozoa, and fungi that efficiently oxidize organic pollutants using oxygen. AGS systems are adaptable to various wastewater conditions, making them suitable for treating various industrial effluents with fluctuating characteristics (de Carvalho et al. 2021).

3.1.1a. Mechanism of Phosphorus Removal and Nutrient Removal Efficiency

AGS systems facilitate Phosphorus removal from wastewater through various mechanisms, including biological uptake by phosphate-accumulating organisms (PAOs) within the granules. Phosphate-accumulating organisms (PAOs) store phosphorus as intracellular polyphosphate and remove it with excess sludge. Aerobic granular sludge simplifies the Enhanced Biological Phosphorus Removal (EBPR) process within sequencing batch reactors (SBRs), ensuring efficient phosphorus elimination from wastewater. It is highly effective at successfully removing carbon and nutrients, essential components in wastewater treatment, this helps prevent environmental contamination and safeguard aquatic ecosystems. This approach reduces the discharge of nutrients, such as Phosphorus, which can contribute to issues like eutrophication in receiving waters. The AGS system achieves this through the formation of microbial aggregates, the production of extracellular polysaccharides (EPS), and the stabilization provided by hydrodynamic shear forces (de Sousa Rollemberg et al. 2018).

3.1.1b. Comparison with Conventional Activated Sludge and Operational Considerations

Compared to the Conventional Activated Sludge System (CAS), Aerobic Granular Sludge (AGS) offers several significant advantages. AGS forms larger and denser sludge granules, typically exceeding 0.2 mm in diameter, which allows for faster settling rates ranging from 30 to 90 meters per hour. This improved settling capacity makes AGS more resilient to toxic substances, enhancing its ability to withstand fluctuating wastewater conditions (de Carvalho et al. 2021). Additionally, AGS is considerably more efficient in terms of resource usage. It requires 75% less land area, consumes 30-50% less energy, and produces 30% less sludge, making it a more sustainable and cost-effective wastewater treatment solution (de Carvalho et al. 2021; Hamza et al. 2022). Overall, AGS technology offers a promising approach for efficient phosphorus removal from industrial wastewater while providing advantages such as reduced footprint, enhanced nutrient removal, and lower operational costs. It is important to note that the successful implementation of AGS technology requires careful design, operation, and monitoring to achieve the desired treatment goals. Furthermore, recent studies have shown SBR's ability to simultaneously nitrify, denitrify, and remove Phosphorus under low-temperature conditions at 10 °C, with overall Phosphorus removal efficiencies up to 98 % (Hamza et al. 2022; Li et al. 2019). AGS systems require monitoring and adjusting operating parameters, such as dissolved oxygen levels, pH, and nutrition management, for optimal functioning. Advanced process control technologies can enhance the accuracy of treatment process modifications.

3.1.2. Enhanced biological phosphorus removal (EBPR) and recovery

Henze et al. (2008) noted that Enhanced Biological Phosphorus Removal (EBPR) systems, developed in the late 1950s, became a widely adopted method for phosphorus removal due to growing concerns about eutrophication.

3.1.2a. Role of Polyphosphate-Accumulating Organisms (PAOs) in EBPR Systems

EBPR is a commonly used technology in CAS systems for phosphorus (P) removal in wastewater treatment plants (WWTPs) (Izadi et al. 2021). The success of EBPR relies on enriching polyphosphate-accumulating organisms (PAOs) in activated sludge. Key PAOs include Pseudomonas putida, Aeromonas spp., Candidatus Halomonas Phosphatis, Candidatus Accumulibacter Phosphatis, and members of the Rhodocyclus genus key bacterial groups involved in enhanced biological phosphorus removal (EBPR) systems. Among them, Candidatus Accumulibacter Phosphatis is the most prevalent and plays the most critical role in phosphorus uptake and storage, making it the primary polyphosphate-accumulating organism (PAO) in these systems (Joshi & Sharma, 2025; Liu et al. 2019; Bunce et al. 2018). Polyphosphate-accumulating organisms (PAOs) remove phosphorus from wastewater through luxury uptake by cycling between anaerobic and aerobic conditions. In the anaerobic phase, they absorb volatile fatty acids (VFAs), storing them as energy reserves while releasing some phosphorus. During the aerobic phase, they use this stored energy to absorb large amounts of phosphorus, enhancing removal efficiency.

3.1.2b. Biochemical Mechanisms of EBPR: Anaerobic and Aerobic Phases

Based on the Accumulibacter biochemical model, enhanced biological phosphorus removal (EBPR) occurs through alternating anaerobic and aerobic (or anoxic) phases governed by the metabolic activity of polyphosphate-accumulating organisms (PAOs). Figure 2 illustrates the transformation of key intracellular polymers—polyphosphate (poly-P), polyhydroxyalkanoates (PHA), and glycogen—highlighting the coupling between carbon uptake, energy generation, and phosphorus release and uptake (Henze et al. 2008).

Under anaerobic conditions (Fig. 2a), PAOs uptake volatile fatty acids (VFAs), such as acetate and propionate, and store them as PHA (e.g., poly-β-hydroxybutyrate and poly-β-hydroxyvalerate). This uptake is driven by the hydrolysis of intracellular poly-P, resulting in the release of orthophosphate (PO_4^{3-}) into the bulk liquid, while glycogen degradation provides the reducing power required for PHA synthesis.

During the subsequent aerobic phase (Fig. 2b), stored PHA is oxidized to generate energy through the tricarboxylic acid (TCA) cycle. The resulting ATP supports cellular growth, replenishment of glycogen reserves, and enhanced phosphorus uptake, leading to the re-accumulation of poly-P within the cells. Under anoxic conditions, certain clades of Accumulibacter can utilize nitrate or nitrite as electron acceptors, enabling simultaneous denitrification and phosphorus uptake using PHA as the carbon source (Henze et al. 2008).

Overall, the mechanism illustrated in Figure 2 emphasizes that EBPR performance is strongly dependent on the availability of readily biodegradable carbon sources and stable redox cycling conditions.

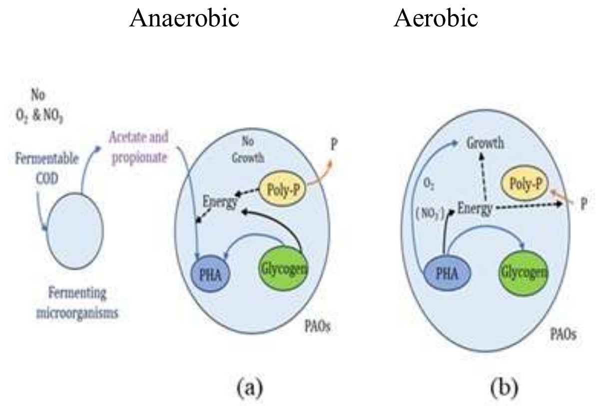


Fig. 2: Biochemical Model of PAOs Under Anaerobic and Aerobic Conditions (Henze et al. 2008)

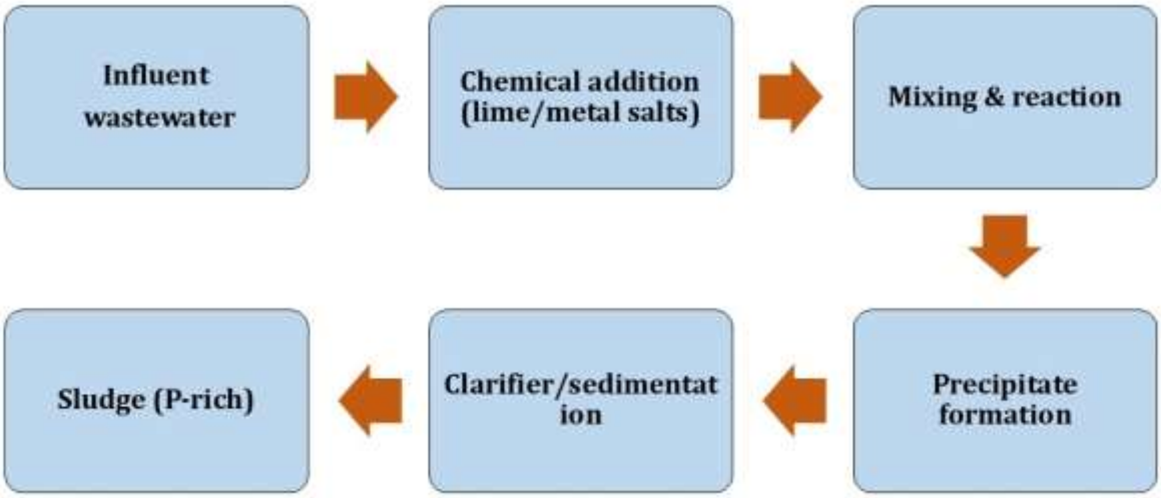
3.1.2c. Challenges and Optimization Strategies for EBPR Systems

Despite its advantages, EBPR faces operational challenges that impact P-removal efficiency. Various factors, including temperature, pH, salt concentration, organic loading rate, wastewater substrate composition, and aeration control, influence the effectiveness of the process (Hamza et al. 2022). Rapid fluctuations in chemical oxygen demand (COD) can negatively impact the aerobic phase, with studies showing that excess COD can cause unintended phosphorus release under aerobic conditions (Guisasola et al. 2019). In anaerobic conditions, high nitrite, nitrate, and ammonia concentrations further disadvantage PAOs, leading to EBPR failure (Zhang et al. 2013). Researchers have applied metabolic modeling techniques to simulate anaerobic and aerobic metabolisms under various control factors, aiming to optimize EBPR performance and enhance PAO dominance over GAOs (Izadi et al. 2021).

3.2. Chemical precipitation

Chemical precipitation is one of the primary commercial methods for phosphorus removal from wastewater effluents. Operators add soluble chemical agents, such as iron, aluminum, or lime, to wastewater. These agents react with phosphate compounds and form insoluble phosphates, which operators remove from the water. While biological removal processes exist, they are used to a lesser extent (Donnert & Salecker, 1999; Penetra et al. 1999; Stratful et al. 1999). The effectiveness of chemical precipitation depends on factors like molar ratio, pH, and hydraulic retention time (HRT), which influence the crystallization of phosphate ions (PO_4^{3-}) into solid forms (Mehta et al., 2015). Recovery efficiencies range between 63% and 99%, with an average removal rate of 81% for Dissolved Nutrient Removal Processes (DNRP). Inorganic polyphosphate demonstrates a high retention rate of 92%, while organic Phosphorus exhibits a slightly lower retention rate of 74%, indicating the need for additional treatment in some cases (Abel-Denee et al. 2018).

Flow Chart: Phosphorus Removal Using Chemical Precipitation



3.2a. Chemical Agents and Their Effectiveness

The choice of precipitating agents is crucial for optimizing phosphorus removal efficiency. Commonly used chemicals include metallic salts such as aluminum, iron, magnesium, and calcium compounds in chloride or sulfate forms (Yin et al. 2020). Selecting a specific chemical depends on wastewater characteristics, including pH, temperature, and desired removal efficiency. Calcium phosphate typically crystallizes into hydroxyapatite (HAP), with the chemical formula $Ca_5(PO_4)_3OH$, whereas magnesium phosphate tends to form struvite ($MgNH_4PO_4 \cdot 6H_2O$) during the crystallization process. Additional chemicals, such as potassium ferrate (K_2FeO_4) and iron chloride ($FeCl_3$), have also been employed. Studies have shown that potassium ferrate doses between 5 and 25 mg/L can retain over 80% of total Phosphorus (TP) (Muster et al. 2013; Kwon et al. 2014; Peng et al. 2018). For struvite precipitation, magnesium sources include $MgCl_2$, MgO, and Mg $(OH)_2$, as well as alternative sources such as seawater and industrial wastewater from frozen fish processing plants (Nur et al. 2018; Huang et al. 2015; Hutnik et al. 2013; Crutchik & Garrido, 2011; Wilsenach et al. 2007; Nelson et al. 2003).

3.2b. Efficiency and Optimization of Phosphorus Recovery

Struvite precipitation is considered highly effective for phosphorus recovery due to its high purity (97–99%) and bioavailability (94%), making it comparable to premium-grade fertilizers (Melia et al. 2017). Maintaining the Mg: Ca ratio at 4:1 with a pH of 7.9 can produce struvite purity exceeding 98%. However, deviations in pH (below 7.5) or changes in the Mg: Ca ratio can introduce impurities (Muster et al. 2013). Various studies have demonstrated high efficiencies in phosphorus recovery through optimized molar ratios. For instance, Nelson et al. (2003) and Kim et al. (2017) achieved 95% efficiency with Mg:P molar ratios of 1.6:1 and 1.2:1.1, respectively. Similarly, Dai et al. (2017) reported an 86% precipitation efficiency for HAP with a Ca:P molar ratio 2.5. Furthermore, electrodialysis has been explored for phosphorus recovery, with Ebbers et al. (2015) achieving 95% recovery at a low pH of 2.0. However, this method has drawbacks, including high energy consumption (1 kWh per 60 g of PO_4 recovery) and the need for chemical additives to regenerate membranes. These findings underscore the importance of tailored strategies to optimize phosphorus removal while balancing cost, efficiency, and environmental sustainability.

3.2.1. The process of lime precipitation

Lime precipitation is a well-established method for wastewater treatment, particularly for the removal of phosphorus. The process is based on chemical interactions between calcium salts and phosphate species present in sewage. These reactions result in the formation of insoluble hydroxy phosphate lime precipitates, which can be readily separated from the aqueous phase. This reaction effectively removes Phosphorus from the water, helping to reduce phosphorus levels in the treated wastewater, which is vital for environmental and water quality management. The reaction equations illustrating as:

$$5Ca^{2+} + 4OH^- + 3HPO_4^{2-} \rightarrow Ca_5(OH)(PO_4)_3 \downarrow +3H_2 ---(i)$$

$$Ca^{2+} + HCO^{3-} + OH^- \rightarrow CaCO_3 \downarrow +H_2O ----------(ii)$$

Following the introduction of lime into phosphorus-containing wastewater, calcium carbonate is initially precipitated through the reaction of calcium ions with bicarbonate ions (Equation ii). Subsequently, the excess calcium ions react with phosphate ions, resulting in the formation of hydroxy phosphate lime precipitate (Equation i). The precipitation process is strongly influenced by the presence of hydroxide ions, which are closely associated with the system's pH. Elevated pH values increase ionic concentrations in solution, thereby reducing the solubility of hydroxy phosphate lime and enhancing its precipitation. For optimal phosphorus removal, it is recommended that the pH be maintained above 10, as this condition favors the formation of hydroxy phosphate lime and significantly improves overall treatment efficiency (Zhou et al. 2008).

3.2.2. Metal salt precipitation

Phosphorus removal from water through metal salts, primarily aluminum and iron salts, involves a chemical process known as coagulation and precipitation. When phosphate ions in water react with introduced metal salts, they form larger, insoluble particles. These insoluble particles effectively trap and encapsulate the phosphorus present in the water. Subsequently, the process involves the separation and removal of these particles, which results in the successful elimination of Phosphorus from the water. This process is a common and effective method for reducing phosphorus levels in wastewater and surface water, helping to mitigate issues like eutrophication and pollution. The choice of metal salt and the specific conditions of the treatment process can be adjusted to optimize phosphorus removal based on the water's characteristics. The reaction equations illustrating the precipitation behaviors of iron salts and aluminum salts are as follows:

$$Fe^{3+} + PO_4^{3-} \rightarrow FePO_4 \downarrow --------(iii)$$

$$3Fe^{2+} + 2PO_4^{3-} \rightarrow Fe_3(PO_4)_2 \downarrow ----\ (iv)$$

$$Al^{3+} + 2PO_4^{3-} \rightarrow AlPO_4 \downarrow --------\ (v)$$

The above main reaction will also occur as a competitive reaction:

$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 \downarrow ------\ (vi)$$

$$Al^{3+} + 3OH^- \rightarrow Al(OH)_3 \downarrow -------\ (vii)$$

The described process involves the precipitation of insoluble phosphate compounds from phosphorus-containing sewage using metal salts, particularly Fe (III) and Al (III) salts. Adding metal salts containing Fe (III) or Al (III) causes the metal ions to react with phosphate ions, forming insoluble phosphate compounds (phosphate precipitate). When salts of Fe (III) are added to sewage, the Fe^{3+} ions react with phosphate ions (PO_4^{3-}) to form insoluble ferric phosphate, $FePO_4$ (Eq. iii). Similarly, Fe^{2+} ions can also react with phosphate to produce ferrous phosphate, $Fe_3(PO_4)_2$ (Eq. iv). Likewise, Al^{3+} ions precipitate phosphate as aluminum phosphate, $AlPO_4$ (Eq. v). These insoluble metal phosphates separate readily from the liquid phase, allowing for effective phosphate removal. These insoluble metal phosphates separate readily from the liquid phase, allowing for effective phosphate removal.

In addition to forming phosphates, Fe (III) and Al (III) ions also undergo competitive reactions with hydroxide ions present in the sewage. For example, Fe^{3+} reacts with hydroxide to form ferric hydroxide, Fe $(OH)_3$ (Eq. vi), while Al^{3+} forms aluminum hydroxide, Al $(OH)_3$ (Eq. vii). These hydroxides are typically amorphous, gel-like precipitates with a large surface area. Importantly, they can adsorb phosphate ions and other impurities from the water. This adsorption plays a central role in the flocculation process, where suspended particles and impurities aggregate into larger flocs that settle out, thereby simplifying solid-liquid separation.

The efficient phosphorus removal achieved a recovery rate of approximately 75%. However, pH levels significantly influence the process. Due to the elevated operational expenses, substantial investment in chemical agents is necessary. Generating a considerable volume of sludge is challenging and contributes to secondary environmental pollution. However, the process is not limited to simple phosphate precipitation. It also involves the formation of metal hydroxides and their subsequent role in flocculation. Combining chemical reactions and physical processes helps efficiently remove phosphates and suspended particles, making it an effective method for treating sewage with high phosphate content (Tuszynska et al. 2013; ZHANG et al. 2013).

3.3. Struvite Crystallization

Struvite crystallization is a recovery-oriented technology that enables simultaneous removal and reuse of phosphorus and nitrogen in the form of magnesium ammonium phosphate ($MgNH_4PO_4.6H_2O$). The process occurs under supersaturated conditions when magnesium, ammonium, and phosphate ions combine in approximately equimolar ratios (Le Corre et al. 2009).

Figure 3 presents the schematic configuration of a struvite crystallization reactor, highlighting key operational components such as mixing, aeration, and controlled chemical dosing. The figure demonstrates how supersaturation and pH control facilitate nucleation and crystal growth, enabling efficient phosphorus recovery.

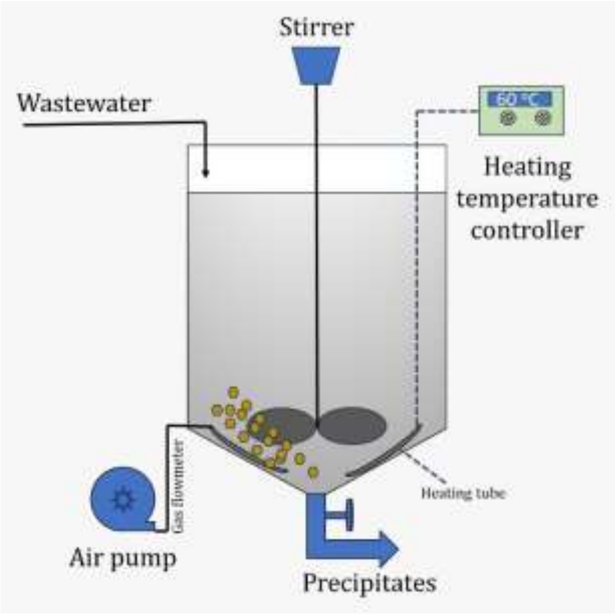


Fig. 3: Schematic diagram of the integrated reactor for struvite precipitation and recovery. (Huang et al. 2015)

Additionally, it contains lower levels of heavy metals than phosphate rock, making it a safer and more sustainable alternative for agricultural use (Suzuki et al. 2002; Yetilmezsoy & Sapci-Zengin, 2009). The schematic diagram of this process is shown in Fig. 3.

Operational parameters such as pH (typically 8–9.5), Mg ratio, temperature, and the presence of competing ions significantly influence crystallization efficiency. For example, calcium ions may lead to the formation of competing precipitates, reducing struvite purity (Hao et al. 2013). In many industrial wastewaters, including slaughterhouse effluents, external magnesium supplementation is required to achieve optimal recovery.

Struvite crystallization offers several advantages, including high recovery efficiency (>90%) and production of a slow-release fertilizer suitable for agricultural use (Cordell et al. 2009). However, the process is constrained by operational complexity, sensitivity to influent composition, and economic challenges associated with reagent costs.

Critically, struvite crystallization represents one of the most effective pathways for circular phosphorus management, but its performance is highly site-specific. Therefore, its integration with upstream processes such as EBPR or anaerobic digestion is essential to ensure sufficient nutrient concentrations and improve overall feasibility.

3.3.1. Mechanisms of Struvite Crystallization

Struvite crystallization occurs when magnesium (Mg^{2+}), ammonium (NH_4^+), and phosphate (PO_4^{3-}) ions are present in solution at supersaturated conditions, leading to the formation of struvite crystals (Le Corre et al. 2009). The chemical reaction occurs as follows:

$$Mg^{2+} + NH_4{}^{+} + \mathrm{PO_4}{}^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O - - - (viii)$$

Struvite formation is influenced by several factors, including the mass ratio of Mg: NH_4:P, pH, temperature, and impurities (Münch & Barr, 2001). The most suitable pH for struvite crystallization is typically between 8.0 and 9.5, as higher pH levels favor the formation of struvite (Doyle & Parsons, 2002). Temperature also plays a critical role, with higher temperatures increasing the crystallization rate (Lee et al. 2009). Supersaturation is a key driver of struvite formation, and controlling supersaturation levels is essential for optimizing size and quality of the crystals (Muhmood et al. 2019). Additionally, the presence of competing ions, such as calcium, can lead to the formation of unwanted byproducts like calcium phosphate, which complicates the recovery process (Hao et al. 2013). Slaughterhouse wastewater typically has a low magnesium (Mg) content, necessitating the addition of an adequate amount of a suitable source of magnesium to facilitate the precipitation of struvite crystals. Magnesium chloride ($MgCl_2$) is a commonly employed magnesium source due to its rapid dissociation characteristics (Suzuki et al. 2005; Liu et al. 2008). Aeration can adjust pH levels, but it typically requires longer residence time. This method effectively increases the pH, making it more alkaline due to introducing oxygen, which can lead to removing acidic components in a study, investigating the impact of varying aeration rates on the process of struvite crystallization, and determining the ideal aeration rates and molar ratios of magnesium to Phosphorus for swine wastewater in order to promote the optimal formation of struvite. The experiment successfully removed over 90% of phosphate and produced more than 60% struvite under various conditions. The pH level played a significant role in determining the outcomes of this process, as indicated by the use of response surface modeling. By controlling and optimizing the pH within a specific range, they achieved high phosphate removal and struvite production rates, highlighting the importance of pH in this chemical process (Saidou et al. 2009; McIntosh et al. 2022; Pastor et al. 2010). Cañas et al. (2023) demonstrated that wet oxidation (WO) of sewage sludge enables efficient phosphorus recovery for circular resource use. From the liquid fraction, orthophosphates (~86 mg P/L) were recovered as high-purity struvite with >95% efficiency, while the solid fraction (~68 mg P/g) achieved up to 63% recovery through acid leaching, with sulfuric acid and dilute HCl being the most effective. Overall, WO reduces organic load and pathogens while maximizing phosphorus recovery, underscoring its potential as a sustainable pretreatment for nutrient recycling.

3.3.2. Applications of Struvite Crystallization

Struvite crystallization in wastewater treatment recovers Phosphorus and nitrogen from anaerobic digester effluents, reducing nutrient pollution and preventing pipeline scaling (Shu et al. 2006). As a slow-release fertilizer, struvite supplies essential nutrients to plants, decreasing reliance on synthetic fertilizers and supporting sustainable agriculture. Additionally, its recovery aligns with the circular economy by recycling valuable nutrients, which is crucial given the diminishing availability of phosphate rock, the primary phosphorus source for fertilizers (Cordell et al. 2009).

3.3.3. Challenges in Struvite Crystallization

Despite its potential, struvite crystallization faces several challenges, including economic viability, as the cost of magnesium sources can hinder widespread adoption (Muster et al., 2013). Operational complexity also poses difficulties, requiring precise control of pH and supersaturation for effective crystallization (Kataki et al., 2016). Additionally, impurities such as heavy metals and organic matter in wastewater can compromise struvite quality, limiting its use as a fertilizer (Hao et al., 2013). Furthermore, regulatory barriers, including the lack of standardized guidelines for struvite-based fertilizers in some regions, restrict commercialization and broader implementation.

By controlling struvite production, researchers can manage and utilize the mineral for several beneficial applications, such as recovering Phosphorus from wastewater and producing valuable fertilizer. Uncontrolled struvite precipitation, on the contrary, can be hazardous in various industrial and natural environments, causing equipment fouling and other concerns.

3.4. Electrocoagulation (EC) removal of phosphorous

Electrocoagulation (EC) is an efficient electrochemical technique for phosphorus removal, achieving removal efficiencies in the range of 85–99%. The process relies on the in-situ dissolution of sacrificial electrodes (typically Fe or Al), generating metal cations and hydroxyl species that facilitate the coagulation and precipitation of phosphate as insoluble metal phosphates. Compared to conventional chemical precipitation, EC reduces external chemical inputs and sludge volume; however, it remains constrained by electrode consumption, energy demand, and limited phosphorus recovery, as most phosphorus is retained in sludge matrices.

3.4.1. Mechanism of Electrocoagulation in Phosphorus Removal

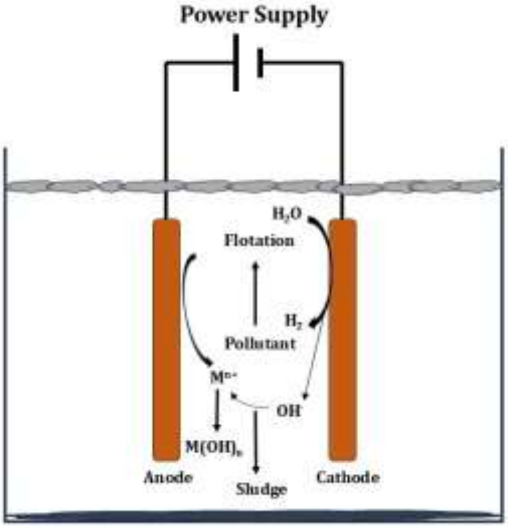


Fig. 4: Electrocoagulation setup (Li et al., 2024)

The pathway for phosphate removal encompasses numerous significant chemical processes occurring at the surfaces of the anode and cathode (for illustration, we use the Fe electrode):

At anode:

$$Fe(s) \rightarrow Fe^{2+}(aq) + \ 2e^{-} ---------- (ix)$$

$$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) \ + \ e^{-} ---------(x)$$

At cathode:

$$2H_2O + 2e^{-} \rightarrow \ H_2 + 2OH^{-} ---------- (xi)$$

Bulk solution:

$$3Fe^{2+}(aq) + 2{PO_4}^{3-}(aq) \rightarrow Fe_3(PO_4)_2(s) --- (xii)$$

$$Fe^{3+} \ (aq) + 2{PO_4}^{3-} \rightarrow FePO_4(s) ------- (xiii)$$

The electrocoagulation mechanism involves anodic dissolution of metal electrodes and cathodic generation of hydroxyl ions, leading to the formation of metal hydroxides that act as coagulants. These species adsorb and precipitate phosphate ions, enabling their removal from solution (Nguyen et al., 2016).

Figure 4 illustrates the EC setup and highlights the fundamental electrochemical reactions occurring at the electrode surfaces. The figure demonstrates how metal ions released from the anode interact with phosphate in the bulk solution, forming flocs that can be separated by sedimentation or flotation. This visualization emphasizes the advantage of EC in generating coagulants in situ, thereby eliminating the need for external chemical dosing and enhancing process efficiency.

Despite these advantages, the inherent limitation of EC: phosphorus is primarily transferred to sludge rather than directly recovered in a reusable form. To address this, post-treatment strategies such as thermal treatment and acid leaching have been explored. For instance, phosphorus-rich sludge obtained after EC can be thermally treated (up to 900 °C) and subsequently leached to recover phosphorus in soluble form (Inna et al., 2025). Similarly, Damaraju et al. (2019) reported that continuous bipolar electrocoagulation removed 73% phosphorus from palm oil mill effluent, with subsequent acid leaching achieving recovery efficiencies of up to 85%.

Overall, while EC is highly effective for phosphorus removal, its sustainability is limited by recovery inefficiencies, highlighting the need for integration with downstream recovery processes such as crystallization or hybrid electrochemical systems.

3.4.2. Industrial Applications and Future Prospects

Electrocoagulation is increasingly being adopted in industrial wastewater treatment due to its cost-effectiveness, low chemical requirement, and minimal sludge generation. A recent study evaluated the feasibility of electrocoagulation combined with electro-advanced oxidation (EC/EAO) for treating abattoir effluent, consistently achieving 99% phosphorus removal (Nidheesh et al., 2022). This advancement underscores the viability of EC-based technologies in mitigating the environmental impact of meat processing industries. Additionally, Khennoussi et al. reported a 95.4% orthophosphate removal efficiency in municipal slaughterhouse wastewater, further confirming the technology's robustness in various wastewater treatment contexts. Given the growing environmental concerns regarding phosphorus pollution, the continuous optimization of EC processes, including novel electrode designs and hybrid treatment approaches, holds promise for sustainable water treatment solutions in industrial and municipal applications.

Additionally, BOD (97%), Fecal Coliform (100%), and TSS (85%) were efficiently removed. Electrocoagulation demonstrated significant color removal, complete disinfection, and TSS removal (>88%) (Kothari et al. 2024). This process consistently achieved a remarkable 99% removal of phosphorus. Khennoussi et al. also reported significant success, with removal rates of 95.4% for orthophosphate when treating wastewater from municipal slaughterhouses (Nidheesh et al., 2022).

Electrocoagulation (EC) and electrocoagulation/electrooxidation (EC/EAO) technologies are cost-effective, sustainable solutions for efficiently reducing phosphate content in wastewater, essential for protecting water quality and minimizing environmental impact. EC serves as a compelling alternative to traditional chemical precipitation, offering high efficiency, environmental friendliness, and cost-effectiveness in removing phosphorus and other inorganic pollutants. Ongoing research and technological advancements continue to expand its applicability across diverse industrial and municipal wastewater treatment scenarios, solidifying its role as a key solution for sustainable wastewater management and improved water quality.

3.5. Phosphorus Recovery in Bioelectrochemical Systems (BES)

Bioelectrochemical systems (BES) have emerged as an innovative approach for phosphorus recovery by integrating microbial metabolism with electrochemical processes. These systems enable simultaneous nutrient recovery and energy generation, making them attractive for sustainable wastewater treatment.

Figure 5 illustrates the key mechanisms governing phosphorus recovery in BES, including electrochemical iron reduction and struvite precipitation. The figure highlights the coupling between anodic oxidation of organic matter and cathodic reactions that create localized conditions favorable for phosphorus mobilization and recovery.

Two primary mechanisms contribute to phosphorus recovery in BES. The first involves cathodic reduction of iron-bound phosphorus (Fe–P). Electrons generated from microbial oxidation of organic substrates at the anode are transferred to the cathode, where Fe(III) is reduced to Fe(II), resulting in the dissolution of Fe–P complexes and release of soluble phosphate into the system. This process may occur via direct electron transfer or through redox mediators (Fischer et al., 2011; Nancharaiah et al., 2016). The second mechanism involves struvite (MgNH4PO4·6H2O) precipitation at the cathode. During BES operation, cathodic reactions generate alkaline conditions (pH ~9–10), promoting the migration of ammonium ions and facilitating struvite crystallization in the presence of magnesium. Since wastewater typically contains sufficient ammonium and phosphate, external magnesium supplementation is often required to achieve optimal recovery (Ichihashi & Hirooka, 2012; Kelly et al., 2014).

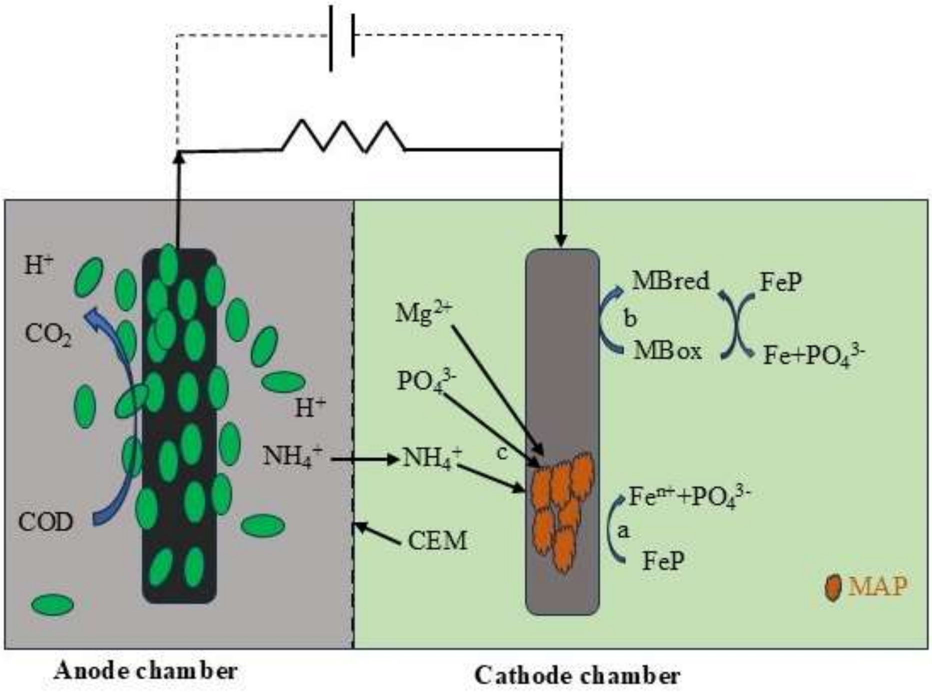


Fig. 5: Phosphorus removal in BES proceeds via three mechanisms: (a) direct reduction of iron, which releases phosphorus from iron phosphate (FeP); (b) indirect iron reduction through redox mediators such as methylene blue (MB); and (c) precipitation of magnesium ammonium phosphate (MAP) formed by the interaction of magnesium, ammonium, and phosphorus. CEM: cation exchange membrane (Nancharaiah et al., 2016).

3.5.1 Phosphorus Recovery from Sewage Sludge

Digested sewage sludge, containing approximately 2–3% phosphorus by dry weight, represents a significant secondary phosphorus resource. BES-based systems enable the mobilization of phosphorus from iron-bound fractions in sludge through cathodic reduction processes. Studies using microbial fuel cells (MFCs) have demonstrated that the addition of redox mediators (e.g., methylene blue) enhances electron transfer, facilitating phosphorus release and subsequent recovery as struvite upon addition of magnesium and ammonium (Happe et al., 2016; Nancharaiah et al., 2016).

In microbial electrolysis cells (MECs), the application of an external voltage improves cathodic reduction efficiency, resulting in enhanced phosphorus solubilization compared to conventional MFC systems. This highlights the importance of system configuration in optimizing phosphorus recovery performance.

3.5.2 Struvite Recovery in BES

BES provide a controlled electrochemical environment that promotes struvite crystallization directly at the cathode surface. Early studies reported phosphorus recovery efficiencies of 48–82% in MFC systems, where insoluble phosphorus was converted into bioavailable forms (Fischer et al., 2011).

In MEC configurations, hydrogen evolution at the cathode further increases local pH, enhancing precipitation kinetics and enabling phosphorus removal rates of up to 40%, with crystallization rates ranging from 0.3 to 0.9 g m^{-2} h^{-1} (Cusick & Logan, 2012). Single-chamber MFCs have demonstrated even higher recovery efficiencies, reaching up to 94.6% in urine treatment and 70–82% removal from wastewater streams, with struvite deposition primarily occurring on cathode surfaces (Ichihashi & Hirooka, 2012; Kelly et al., 2014).

3.5.3 Photosynthetic BES for Nutrient Recovery

Photosynthetic BES integrate microalgae into the cathodic chamber, enabling simultaneous recovery of phosphorus and nitrogen through biological uptake. In these systems, microalgae utilize nutrients for biomass growth while contributing to oxygen production, enhancing system efficiency.

For example, photomicrobial fuel cells incorporating Chlorella vulgaris have achieved phosphorus removal efficiencies of approximately 70%, along with significant removal of organic carbon (99.6%) and nitrogen (87.6%) (Zhang et al., 2011). Similarly, integrated photo-bioelectrochemical systems have demonstrated phosphate removal efficiencies of up to 82% in algal cathodes (Xiao et al., 2012). Coupling algal bioreactors with MFCs further enhances nutrient recovery, increasing phosphorus removal efficiency from 58% to 92% (Jiang et al., 2012).

However, despite these advantages, challenges remain in biomass harvesting, downstream phosphorus recovery from algal biomass, and maintaining system stability under varying environmental conditions.

Critical Evaluation

From a critical perspective, BES offer significant advantages, including low chemical input, potential energy recovery, and direct phosphorus precipitation. However, their application is limited by low technology readiness level (TRL), high capital costs, electrode and membrane fouling, and operational complexity.

Compared to conventional technologies, BES provide higher recovery potential but lower scalability. This highlights the need for hybrid approaches, such as coupling BES with EBPR or struvite crystallization systems, to enhance overall process efficiency and feasibility.

4. Hybrid and Integrated Phosphorus Recovery Systems

Hybrid treatment systems have emerged as a promising strategy to overcome the limitations of individual phosphorus removal technologies by combining biological, chemical, and electrochemical processes. These integrated approaches enable simultaneous enhancement of removal efficiency, recovery potential, and process stability.

One of the most effective configurations involves coupling Enhanced Biological Phosphorus Removal (EBPR) with downstream struvite crystallization. In such systems, EBPR concentrates phosphorus in sludge or sidestreams, which are subsequently treated under controlled conditions to recover phosphorus as struvite. This approach improves recovery efficiency while reducing chemical demand and sludge handling requirements (Li et al., 2025).

Similarly, electrocoagulation (EC) combined with crystallization has gained attention as a hybrid solution. While EC effectively removes phosphorus by transferring it into sludge, subsequent crystallization or acid leaching processes can convert the immobilized phosphorus into reusable forms. This integration addresses one of the key limitations of EC—low recovery efficiency—by enabling resource recovery from sludge.

Integration of bioelectrochemical systems (BES) with conventional processes represents another emerging pathway. BES can be coupled with EBPR to enhance phosphorus release from sludge, followed by electrochemical precipitation or struvite recovery at the cathode. Such systems offer the potential for simultaneous nutrient recovery and energy generation, although they remain at an early stage of development.

From a process perspective, hybrid systems provide several advantages: Improved phosphorus recovery efficiency, Reduced chemical consumption, Enhanced operational flexibility, Better alignment with circular economy principles.

However, these systems also introduce challenges related to process complexity, capital investment, and system integration. The optimization of operating conditions across multiple units remains a key research requirement.

Overall, hybrid systems represent the most promising approach for sustainable phosphorus management, as they combine the reliability of conventional technologies with the recovery potential of emerging methods.

4.1. Economic feasibility of P recovery

Phosphorus (P) recovery by crystallization, particularly as struvite, has been proven technically feasible and is already operational in Europe, North America, and Asia. Studies show that 1 kg MAP can be recovered from 100 m^3 municipal wastewater (7 mg PO_4^{3-}/L, 55.3% efficiency), and up to 2.58 kg struvite can be obtained from 1 m^3 hydrolyzed urine containing 8.1–19% P. Energy demand varies, with cogeneration systems requiring less power (260 kWh/kg P) than conventional ones (510 kWh/kg P). However, economic feasibility is limited by high operational costs, which range from 2.2–8.8 €/kg P and rise significantly at lower P concentrations (1.6 €/kg P at 120 mg PO_4^{3-}-P/L), while the struvite market value was only 0.38–0.46 €/kg P, insufficient to offset costs. Despite this, P recovery offers key benefits including reduced sludge production, availability of high-quality slow-release fertilizers, and prevention of eutrophication. Thus, while direct economic returns may be limited, environmental advantages and supportive government regulations remain crucial drivers for implementation (Peng et al.,2018).

4.1.1. Economic Feasibility of Phosphorus Recovery Technologies

Economic feasibility remains a critical factor influencing the large-scale adoption of phosphorus recovery technologies. The cost structure of these systems is typically governed by both capital expenditure (CAPEX) and operational expenditure (OPEX), including energy consumption, chemical inputs, maintenance, and sludge handling.

Chemical precipitation is widely implemented due to its low capital cost and operational simplicity; however, its overall cost is dominated by continuous chemical consumption and sludge disposal. Moreover, the lack of direct phosphorus recovery reduces its economic attractiveness in resource recovery frameworks (Zheng et al., 2023).

Electrocoagulation (EC) offers moderate operational costs, with energy consumption typically ranging between 0.05–0.9 kWh m^{-3} depending on wastewater characteristics. However, electrode replacement and electricity demand contribute significantly to OPEX, and the absence of efficient recovery mechanisms limits potential economic returns (Al-Qodah et al. 2025).

Struvite crystallization provides a direct revenue stream through the production of slow-release fertilizers. However, its economic viability is highly dependent on phosphorus concentration and magnesium source cost. Reported operational costs range from 2.2–8.8 €/kg P, often exceeding the market value of recovered struvite (Peng et al. 2018). Consequently, economic benefits are typically realized through indirect savings, such as reduced scaling and sludge handling costs.

Bioelectrochemical systems (BES) remain economically challenging due to high capital costs associated with electrodes, membranes, and system infrastructure. Although BES offers potential energy recovery, current applications are limited to pilot scale, and cost uncertainties remain significant (Corona-Martínez et al. 2025).

From a comparative perspective, a key insight emerges: Technologies with high removal efficiency (e.g., chemical precipitation, EC) often exhibit lower recovery value, whereas recovery-oriented technologies (e.g., struvite, BES) face higher operational and capital costs.

This trade-off highlights the importance of integrated and hybrid systems, which can improve overall economic feasibility by combining removal efficiency with resource recovery. Additionally, policy incentives, environmental regulations, and circular economy frameworks play a crucial role in improving the economic viability of phosphorus recovery technologies.

Future research should focus on cost optimization, alternative low-cost reagents, and lifecycle-based economic assessment to support large-scale implementation.

Industry-Specific Recommendations

Technology selection should align with wastewater characteristics across industries. For food processing and slaughterhouse effluents, struvite crystallization is preferred due to high NH_4^+ content, with electrocoagulation (EC) applied as a polishing step (Zheng et al. 2023).

In dairy and beverage industries, EBPR integrated with sidestream struvite recovery is suitable where anaerobic digestion exists; otherwise, EC is a practical option for smaller facilities.

For the fertilizer industry, high phosphorus concentrations favor advanced recovery methods, such as acid leaching combined with mineral precipitation (struvite/vivianite) (Zheng et al., 2023). In landfill leachate and condensate, high conductivity supports efficient application of electrochemical processes, including EC (Al-Qodah et al. 2025).

Finally, textile and pulp & paper wastewater, typically low in phosphorus but rich in co-contaminants, requires integrated polishing approaches (e.g., adsorption coupled with EC) (Zheng et al. 2023).

4.1.2. Comparative Analysis of Phosphorus Removal and Recovery Technologies

A comparative evaluation of phosphorus removal and recovery technologies highlights clear trade-offs among removal efficiency, recovery potential, cost, and scalability, indicating that no single approach can simultaneously optimize all performance criteria.

Biological processes, particularly Enhanced Biological Phosphorus Removal (EBPR) and aerobic granular sludge (AGS), are cost-effective and environmentally sustainable, achieving phosphorus removal efficiencies of up to 98%. However, their recovery potential remains limited because phosphorus is primarily retained within biomass, requiring additional downstream processing for reuse.

Chemical precipitation is a well-established and reliable method, consistently achieving removal efficiencies in the range of 90–95%. Despite its reliability, the process is associated with high chemical consumption and significant sludge generation, which increases operational costs and environmental burdens.

In contrast, struvite crystallization represents a recovery-oriented approach that enables the conversion of dissolved phosphorus into a high-purity, bioavailable fertilizer. Its performance is strongly dependent on controlled operational conditions, including pH and magnesium-to-phosphate ratios, which can limit its applicability in dilute wastewater streams. Recent advancements, such as the use of low-cost magnesium sources and seeding strategies, have improved process efficiency and reduced operational costs, while additional system-level benefits, including improved sludge dewaterability and reduced polymer demand, have been reported (Santos et al. 2024).

Electrochemical methods, particularly electrocoagulation (EC) and electrochemical precipitation, demonstrate high phosphorus removal efficiencies (85–99%) with reduced reliance on external chemicals due to in-situ coagulant generation. Recent pilot-scale studies report energy consumption in the range of 0.05–0.9 kWh m-3, depending on wastewater characteristics. Nevertheless, challenges such as electrode consumption, energy demand, and moderate phosphorus recovery potential (50–70%) constrain widespread adoption. Emerging hybrid EC–crystallization systems show promise for shifting these processes from removal-focused to recovery-oriented solutions (Shah et al. 2024).

Bioelectrochemical systems (BES) represent an emerging class of technologies that integrate microbial and electrochemical processes to enable phosphorus recovery alongside energy generation. Recovery efficiencies of up to 94.6% have been reported; however, practical implementation remains constrained by high capital costs, membrane fouling, and operational complexity. Recent advances in reactor design, including stacked configurations and selective cathodic precipitation, suggest potential pathways for scale-up (Corona-Martínez et al. 2025).

Recent research trends increasingly emphasize integrated and hybrid approaches. For example, coupling EBPR with anaerobic digestion enhances phosphorus concentration in sidestreams, facilitating efficient downstream recovery through crystallization or electrochemical processes. This “A-stage EBPR + sidestream recovery” framework is emerging as a scalable and resource-efficient strategy for wastewater treatment systems (Li et al., 2025). Such developments reflect a broader transition from conventional “remove-and-dispose” approaches toward resource recovery, reduced chemical dependency, and circular economy integration (Zheng et al., 2023).

Table 2: Comparative Evaluation of Technologies for Phosphorus Removal and Recovery

Technology	Removal Efficiency	Recovery Potential	Cost & Complexity	Scalability (TRL)	Key Limitations
EBPR / Biological	Moderate–High (70–95%)	Moderate (poly-P sludge)	Low–Moderate	High (full-scale)	Sensitive to operational conditions
Chemical Precipitation	High (>90%)	Low–Moderate (metal-P sludge)	Moderate	High	Chemical consumption, sludge generation
Struvite Crystallization	High (for PO_4^{3-})	High (valuable fertilizer)	Moderate	Medium–High	Requires controlled conditions (Mg^{2+}, pH)
Electrocoagulation (EC)	High (>90%)	Low	High (energy demand)	Medium	Electrode consumption, scaling issues
Bioelectrochemical Systems (BES)	Moderate	High (emerging recovery route)	High (R&D stage)	Low–Medium	Limited large-scale validation

Table 3: Technologies for Wastewater Treatment and Resource Recovery

Wastewater	Technology used	Process involved	System conditions	Extracted product	P	References

					Removal/ Recovery	
Biological secondary effluent (BSE)	Fluidized reactor operating under alternative anaerobic/anoxic mode.	Denitrifying phosphorus-removal granular sludge (DPGS)	P input (mg TP/L) =0.54	Granules	74.5%	Chen et al. (2023)
Low-strength wastewater	Continuous-flow reactor based on metabolic and hydraulic selection pressure.	Continuous-flow AGS system		Granules	94.8%	Chen et al. (2024)
Sewage Sludge	Struvite Recovery Reactor	Controlled Struvite Precipitation	pH=7.5to 9.5 Mg/P molar ratio= 1 to 4	Struvite	>95%	Cañas et at. (2023)
Dairy processing wastewater	Struvite Recovery Reactor	Struvite Precipitation	Ph=9–10 10-20°C Mg/P molar ratio ≤ 2	Struvite	Phosphate removal (>90%) and d struvite production (>60%)	McIntosh etal. (2022)
Industrial wastewater	Chemical Precipitation	Chemical added: Seawater–ammonia (Mg^{2+})	Nitrogen:Phosphorus = 4.0:1.0 At pH=8.0–8.5 HRT= 2 h P initial (mg PO_4^{3-}–P/L) =84	Precipitate	64 %	Hermassi et al. (2016)
Fertilizers industry wastewater	Chemical Precipitation	Chemical added: $MgCl^{2-}$ NH_4Cl	Mg:N:P = 1.0:1.0:1.0 pH=8.5-10 HRT(h)= 0.25–1 P input (mg PO_4^{3-}–P/L) =1483	Precipitate	98–99 %	Hutnik et al. (2013)
Anaerobic supernatant	Chemical Precipitation	Chemical added: Metal salts	$Fe^{2+}Fe^{3+}Al^{3+}$:P =	Precipitate	72 % 78 %	Huang et al. (2017)

	Fe^{2+} Fe^{3+} Al^{3+}	1.0:1.0 pH= 6.5, 4.5, 5.0 HRT(h)= 0.5 P input (mg PO_4^{3-}–P/L) =148	87 %

Table 4: Sustainable Advances in Phosphorus Recovery

Technology	**Suitable Waste Streams**	**Recovery vs. Removal**	**Maturity & Scalability**	**Key Sustainability Features**	**Main Cost Drivers**
Struvite crystallization	Food processing, slaughterhouse, digestate, centrate, dairy	Recovery (struvite fertilizer)	Commercial pilots and full-scale in some plants	Improves dewatering, reduces polymer demand; can use waste Mg sources	Mg source cost, scale, product market value
Electrocoagulation (EC) / electro-precipitation	Landfill leachate, metal finishing, high-conductivity effluents	Primarily removal; recovery possible with hybrid EC + crystallization	Pilot to demo scale, modular designs	On-site coagulant generation, avoids chemical transport	Energy use (0.05–0.9 kWh m^{-3}), electrode cost, electricity price
Hybrid EBPR + struvite / EC	Municipal-industrial co-treatment, food sector	Recovery, with higher overall yields	Demonstrated in large WWTPs; growing industrial application	Reduces chemical inputs, leverages biological concentration	Integration complexity, CAPEX for multiple units
Struvite crystallization	Food processing, slaughterhouse, digestate, centrate, dairy	Recovery (struvite fertilizer)	Commercial pilots and full-scale in some plants	Improves dewatering, reduces polymer demand; can use waste Mg sources	Mg source cost, scale, product market value
BES (bioelectrochemical systems)	Niche sidestreams, high-strength organic-P mixtures	Direct recovery at cathode (precipitate)	Low TRL, pilot stacked units emerging	Low reagent needs, partial energy recovery	Scale-up cost, electrode/material durability
Chemical precipitation	Fertilizer/phosphate effluent,	Removal (recovery possible with tailored steps)	Very mature, widely used	Reliable polishing; can be adapted for recovery	Reagent costs, sludge

(e.g., alum, ferric salts)	textile/pulp wastewater				handling/disposal
Vivianite recovery / Fe-based routes	Anaerobic digesters, phosphate industry effluents	Recovery (vivianite mineral)	Early demo stage	Co-recovery of Fe and P, potential market value	Digester iron dosing, separation efficiency

Tables 2–4 collectively provide a comprehensive comparison of phosphorus removal and recovery technologies; however, their integrated interpretation reveals important trade-offs, process dependencies, and practical implications for sustainable wastewater management.

A key insight from Table 2 is the distinction between removal-oriented and recovery-oriented technologies. Conventional methods such as chemical precipitation and electrocoagulation achieve high phosphorus removal efficiencies (>90%), but primarily transfer phosphorus into sludge-bound forms, limiting its direct reuse (Donnert & Salecker, 1999; Nguyen et al., 2016). In contrast, recovery-focused approaches such as struvite crystallization and bioelectrochemical systems (BES) enable the conversion of phosphorus into reusable products, including magnesium ammonium phosphate, thereby supporting resource recovery (Le Corre et al., 2009; Nancharaiah et al., 2016). However, these systems require stricter operational control and exhibit lower technological maturity. This comparison highlights a fundamental limitation: high removal efficiency does not necessarily correspond to high recovery potential.

The role of wastewater characteristics becomes evident in Table 3, where treatment performance varies significantly with influent composition and operating conditions. High-strength waste streams, such as sewage sludge and fertilizer industry effluents, enable higher recovery efficiencies when treated using crystallization-based processes under optimized pH and molar ratios (Hutnik et al., 2013; Cañas et al., 2023). Conversely, low-strength wastewater systems depend more on biological processes, where phosphorus is assimilated into biomass rather than recovered (Chen et al., 2023; Chen et al., 2024). This indicates that recovery technologies are more effective in concentrated sidestreams, while mainstream systems remain largely removal-focused. Additionally, the sensitivity of treatment performance to parameters such as pH, hydraulic retention time, and chemical dosing underscores the need for site-specific optimization (Huang et al., 2017).

Further insights into scalability and sustainability are provided by Table 4, which compares technologies based on maturity, applicability, and operational constraints. Established processes such as EBPR and chemical precipitation exhibit high technology readiness levels and are widely implemented, but are limited in terms of recovery efficiency and long-term sustainability (Zheng et al., 2023). In contrast, emerging technologies such as BES and hybrid systems offer advantages including reduced chemical input and enhanced recovery potential, yet remain constrained by high capital costs, system complexity, and limited full-scale validation (Corona-Martínez et al., 2025). Struvite crystallization occupies an intermediate position, with demonstrated pilot- to full-scale applications and strong alignment with circular economy principles (Santos et al., 2024).

A combined interpretation of Tables 2–4 indicates that phosphorus management technologies must be evaluated across multiple dimensions, including efficiency, recovery potential, cost, and scalability. No single technology achieves optimal performance across all criteria. Instead, integrated systems that combine biological, chemical, and electrochemical processes provide a more balanced and sustainable approach by leveraging the strengths of individual methods (Li et al., 2025).

This synthesis also highlights key research gaps, including the lack of standardized economic evaluation metrics, limited large-scale implementation of emerging technologies, and insufficient integration of recovery processes within existing treatment systems. Addressing these challenges is essential for advancing practical and resource-efficient phosphorus management strategies.

5. Research Gaps and Future Directions

Research Gaps

Despite recent progress, several limitations hinder the practical implementation of phosphorus recovery technologies. A key gap is the absence of standardized metrics for evaluating recovery efficiency, cost, and sustainability, which restricts meaningful comparison across studies. Additionally, emerging technologies such as bioelectrochemical systems (BES) and hybrid processes lack sufficient large-scale validation, limiting their industrial applicability. Current research also underrepresents the role of phosphorus speciation in influencing treatment and recovery performance. Furthermore, comprehensive life cycle assessments are scarce, making it difficult to evaluate the overall environmental sustainability of these technologies.

Addressing these challenges is essential for advancing efficient, scalable, and sustainable phosphorus recovery systems.

Future Directions

Integration and Process Optimization

Future efforts should prioritize the development of hybrid systems that integrate biological (EBPR, AGS), electrochemical (EC, BES), and crystallization processes to enhance phosphorus recovery and overall system efficiency. Coupling BES with struvite crystallization or electrocoagulation can enable continuous recovery while mitigating operational limitations. Additionally, the application of advanced process control (APC) and real-time monitoring can optimize key parameters such as pH, dissolved oxygen, and aeration, ensuring stable and efficient operation.

Microbial and Biochemical Advancements

Improving system performance requires targeted manipulation of microbial communities. Selective enrichment of functional consortia and enhancement of polyphosphate-accumulating organisms (PAOs) and electroactive microbes can improve phosphorus mobilization and recovery. Such advancements are particularly relevant for integrated EBPR–BES systems.

Resource Recovery and Circular Economy

Enhancing the efficiency and purity of struvite crystallization is essential for its large-scale application as a sustainable fertilizer. In parallel, the valorization of phosphorus-rich by-products, such as sludge-derived materials, should be explored to support circular economy approaches and reduce waste generation.

Technological Innovations

Advancements in electrocoagulation, including the development of durable and energy-efficient electrode materials, are needed to improve process performance. Integration of intelligent and automated control systems can further enhance operational efficiency and reduce energy consumption.

Environmental and Economic Assessment

Future research should emphasize comprehensive life cycle assessment (LCA) and techno-economic evaluation to assess the sustainability and feasibility of emerging technologies. Cost reduction strategies, particularly for reagents and energy inputs, are critical for enabling large-scale implementation.

6. Conclusions

This review critically evaluated phosphorus removal and recovery technologies using a multi-criteria framework. Conventional methods such as chemical precipitation and electrocoagulation remain effective for phosphorus removal but provide limited recovery potential and generate secondary waste streams. In contrast, resource-oriented approaches such as struvite crystallization and bioelectrochemical systems (BES) better align with circular economy principles by enabling nutrient recovery, although challenges related to cost, process stability, and scalability persist.

Biological processes, particularly enhanced biological phosphorus removal (EBPR) and aerobic granular sludge (AGS), offer efficient and sustainable treatment options, with AGS demonstrating advantages in settling, footprint, and resilience. However, operational limitations, including substrate variability and microbial competition, can affect system performance. Struvite crystallization presents a viable pathway for simultaneous removal and recovery, while BES technologies provide emerging opportunities for integrated nutrient recovery and sludge reduction.

Overall, no single technology can simultaneously maximize removal efficiency, recovery potential, and economic feasibility. Therefore, integrated and hybrid systems represent the most promising approach for sustainable phosphorus management. Future research should focus on large-scale validation, process optimization, and life-cycle assessment to facilitate the transition toward resource-efficient and circular wastewater treatment systems.

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